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On The Mechanics Of Beam Gauges*

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Abstract
A simple mechanics based understanding of different factors affecting beam-type transducers (beam gauges) used for measuring coil stresses in superconducting magnets has been attained. A finite element model with contact elements and non-linear material behavior corroborated with experimental results is used to develop the understanding. Finite element results indicate that plastic deformation of either the beam or the back plate can cause significant errors in measured stress values. However, the variation in coil modulus does not affect gauge calibration significantly. The current design of the beam gauges has been modified to prevent plastic deformation of the beam and back plates. The implemented design changes include a change in the gauge material from Nitronic 40 steel to Nitronic 50, and a redesign of the back plate to prevent loading it plastically.

1. Introduction

Strain gauge based beam-type transducers (Goodzeit Gauges[1]) have been used since 1989 to measure internal azimuthal compressive coil stresses in superconducting magnets. These transducers are designed to provide improved sensitivity to compressive strains by using bending mode deflections for sensing the applied pressures. Before being put into a magnet, beam gauges are calibrated in a calibration fixture by applying a known pressure through a ten-stack cable to the surface of the beam and measuring the resulting change in the resistance of the strain gauge. A calibration curve can then be obtained which relates resistance-change to the known applied pressure. The internal coil stresses in a magnet can be obtained from the calibration curve by measuring strain gauge resistance change during different stages of magnet assembly and operation.

A reliable measurement of coil stresses depends on calibration methodology that reproduces closely the actual conditions inside a magnet. Several factors that affect calibration are modulus variation of ten-stack, support (boundary) conditions for the beam gauge and non-linear material behavior. Until now there has been no clear quantitative understanding of how these different factors affect calibration. A qualitative

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investigation of factors affecting strain gauge calibration has been performed by Davidson et al.[2] In this investigation, the authors attributed inaccurate calibrations to the bowing of back plates, modulus variation of ten-stack, and damage introduced in the ten-stacks during the cutting process and due to their reuse for several calibrations. However, no quantitative understanding can be derived from this study as to the relative importance of different factors and to the extent of their influence on calibration.

It is the intent of this paper to develop a simple mechanistic based quantitative understanding of beam gauges and understand how different factors affect gauge calibration. A finite element model utilizing contact elements and non-linear material behavior has been set up to investigate the influence of different factors on beam gauge calibration. The model used is verified for its accuracy by simple gauge calibration experiments performed on a well-characterized material. The finite element model is then used as a predictive design tool to implement design changes in the existing beam gauge configuration.

2. Background

Fig. 1 shows a schematic representation of a beam-type transducer. The beam gauge comprises of two plates: a thick flat *beam plate* with strain gauge mounted on it, and a *back plate* which has a notch cut in it to allow bending of the beam plate when load is applied normal to it. When pressure, P is applied normal to the beam plate, the beam undergoes bending deformation leading to change in resistance of the strain gauge mounted on the beam plate. The strain, ε in the beam plate due to bending deformations can be obtained from:

$$\varepsilon = \frac{\Delta R / R}{G.F.},$$

where R is the original strain gauge resistance and $G.F.$ is the gauge factor. The stress in the beam plate is linearly proportional to the measured strain (ε) where the proportionality constant is the Young's modulus (E) of the beam plate material. A calibration curve relating strain to the applied pressure can be obtained through experiments.

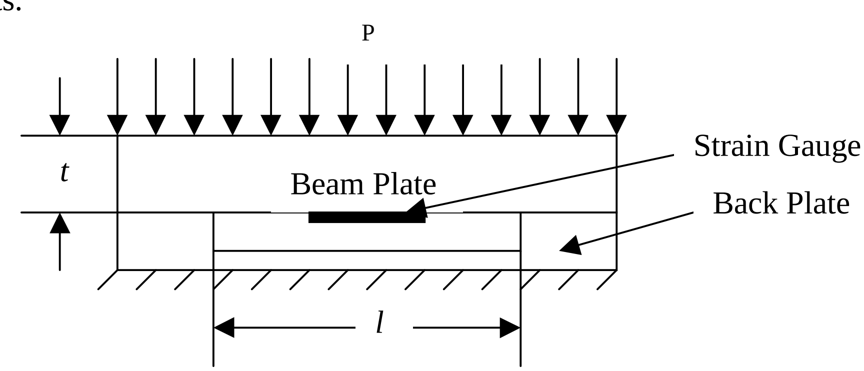

Figure 1: Schematic of a beam gauge. Load P causes change in resistance of the strain gauge due to bending deformations.

If l is the length of the beam plate which can undergo bending deformation and t is the thickness of the beam plate, then an upper and lower bound can be obtained on calibration curve depending on whether the beam has clamped ends or simply supported ends. For clamped ends, the following relationship holds true:

$$\varepsilon = P\frac{l^2}{4Et^2},$$

whereas for simply supported ends the beam strain is related to the applied pressure by the following relationship:

$$\varepsilon = P\frac{3l^2}{4Et^2}.$$

In practice, the calibration curve lies in between the two extremes as shown in Fig. 2 for a fixed value of l and t.

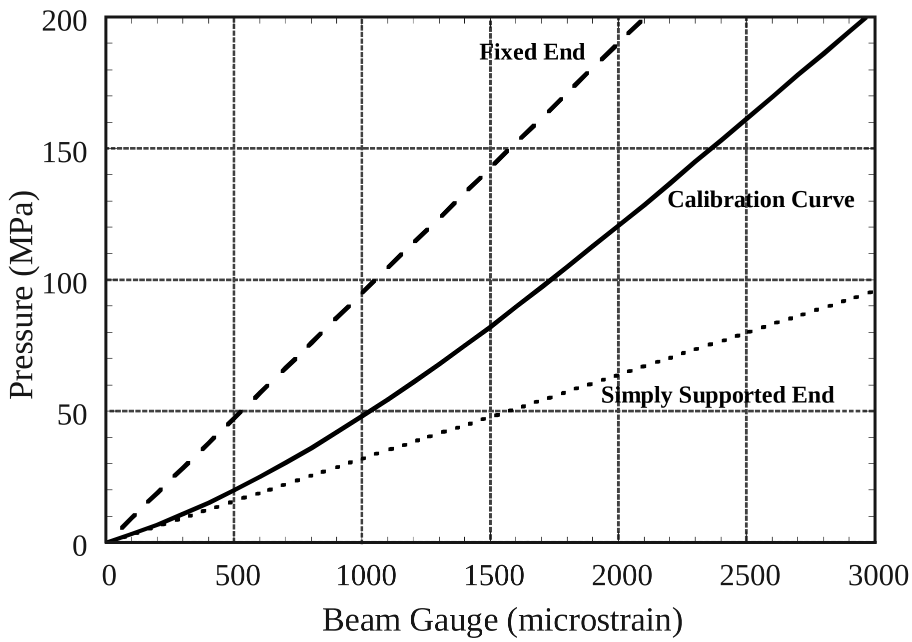

Figure 2: An actual calibration curve compared to theoretical cases of simply supported and fixed ends for the beam plate. The real calibration curve lies in between the two theoretical bounds.

3. Experimental Results

Simple gauge calibration experiments were performed using Ultem 1000 instead of ten-stack cables used for gauges calibrated for use in superconducting magnets. Typical mechanical properties of this material are listed in Table 1.

Tensile Yield Strength	Compressive Strength	Compressive Modulus
105 MPa	151 MPa	3.3 GPa

Table 1: Mechanical properties of Ultem 1000

Ultem 1000 was chosen instead of a ten-stack cable due to its well-characterized linear stress-strain behavior up to yield point and also because its modulus of 3.3 GPa is close to the modulus of 5-10 GPa for coils used in LHC High Gradient Quadrupole magnets. Moreover, apparent hysterisis in the stress-strain behavior observed during repeated loading/unloading of a ten-stack cable is not observed in Ultem 1000. Note that the maximum stress applied to the Ultem block was always below its yield strength so that no plastic deformation should occur in the Ultem.

To understand the role of support (boundary) conditions on gauge calibration, the experiments were performed for two different configurations, as shown in Fig. 3. In the first configuration, the back plate rests on a rigid surface while the load is applied on the beam plate through a block of Ultem. In the second configuration, the back plate rests on an Ultem block while the load is still applied on the beam plate through an Ultem block.

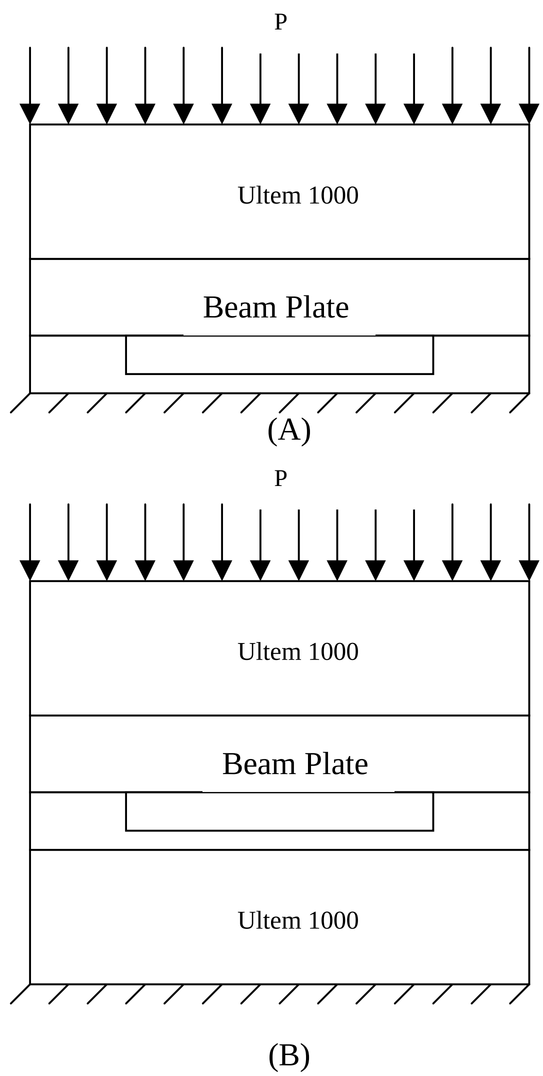

Figure 3: Two different configurations used for calibrating beam gauges to evaluate the influence of supports (boundary conditions) on calibration.

The above two configurations can be thought of as representing two different support conditions for the inner and outer beam gauges used in Fermilab's HGQ magnets. For outer beam gauges, the back plate has a thick steel collar behind it and hence this is closer to configuration *A*. On the other hand, for inner beam gauges the back plate has a very thin layer of steel collar with inner coils behind it. Hence this is closer to configuration *B*.

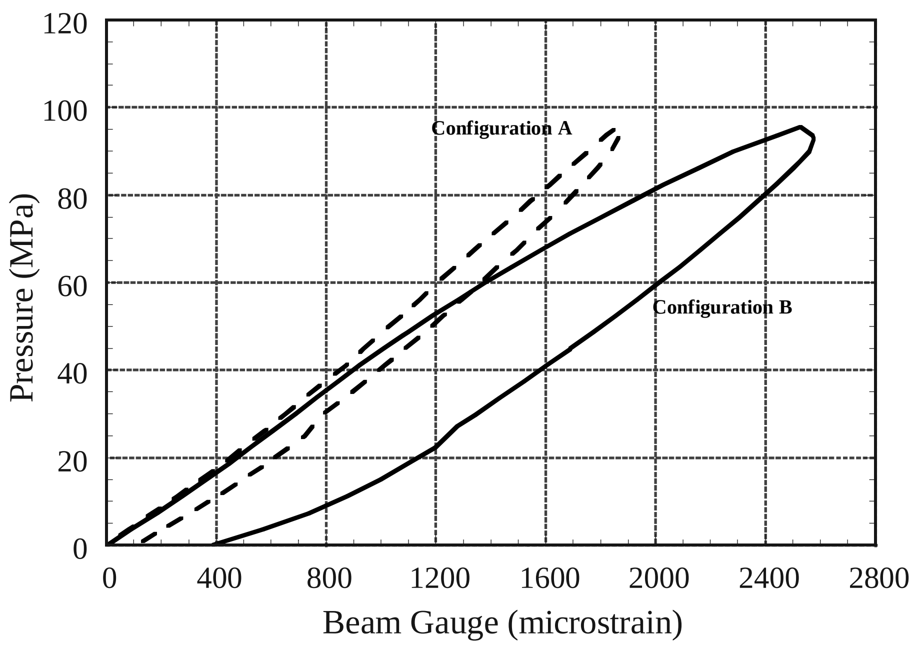

Figure 4: Comparison of calibration curves obtained from two different support conditions.

Fig. 4 shows the experimental calibration curves obtained for the two different configurations shown in Fig. 3. Both loading and unloading behavior are presented in the figure. It is observed that for applied pressures less than 30 MPa, the loading curves for both configurations are almost identical. However, for higher pressures the two loading curves begin to deviate significantly. It is observed that the application of same pressure on the beam plate causes much more bending deformations (and strains) for configuration *B,* where the back plate is not as well supported as that for configuration *A*. This demonstrates the importance of support (boundary) conditions in influencing the calibration behavior. Note that if beam gauges were calibrated in a configuration similar to configuration *A*, whereas in actual operating conditions they operate in a configuration similar to configuration *B*; then very large errors would be obtained in calculated stress values. For example, if the prestress in the coils is 83 MPa and if the gauges are operating in a configuration similar to configuration *B*, then that would indicate a measured strain value of 2000 microstrain. However, if these gauges were calibrated in a configuration similar to configuration *A*, then the calibration curve from configuration *A* would indicate a prestress in the coils of the order of 105 MPa, an error of 27%. Also note that the error increases progressively for higher prestresses.

Note that for both configurations, the unloading does not follow the loading behavior and there is a residual microstrain after complete removal of the applied load. This apparent hysterisis in the loading/unloading behavior is more severe for configuration *B* than for configuration *A*. Also the application of the same load causes much more residual microstrain for configuration *B* than for configuration *A*, after removal of the applied load.

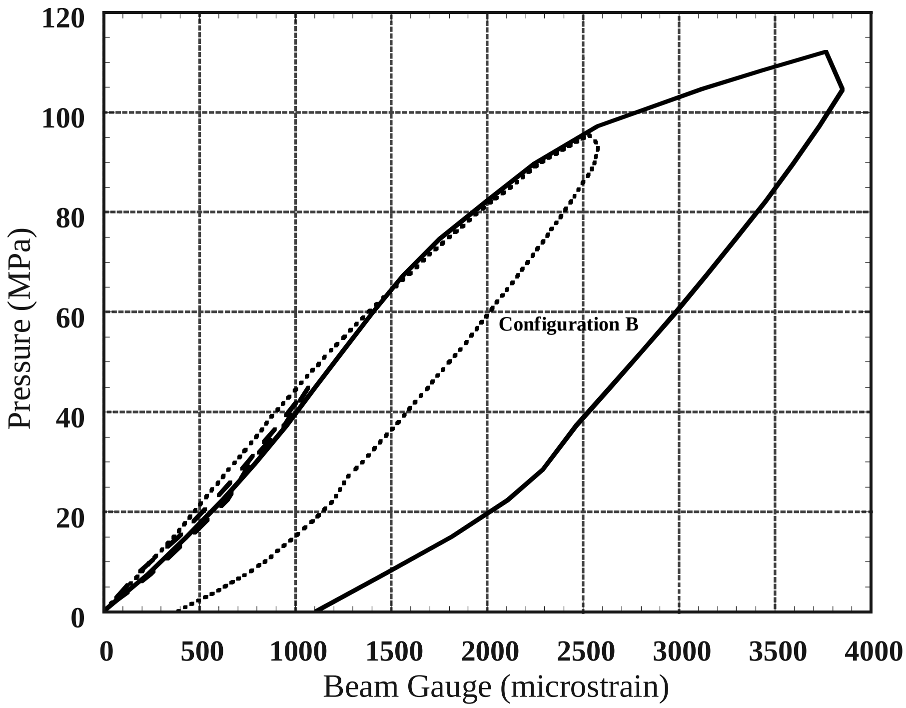

Figure 5: Calibration curves obtained in configuration *B* for three different loading/unloading cycles.

Fig. 5 shows the loading/unloading behavior of a beam gauge for three different loading cycles in configuration B. It is observed that for stress values less than 45 MPa, the unloading follows the loading behavior and there is no residual microstrain after removal of the applied load. However, application of higher loads causes an apparent hysterisis in the behavior with residual microstrain in the beam gauge after load removal. This residual microstrain increases with the increase in the applied load, as observed in Fig. 5.

4. Finite Element Modeling

A two-dimensional finite element model using ANSYS was set up to understand the observed experimental results. Fig. 6 shows a finite element mesh used for beam gauge calibrated in configuration *B*. 2-D plane quadrilateral elements (PLANE 42) were used for the beam and back plates and for ultem blocks. All contact surfaces were modeled using CONTAC 48 contact elements. The beam and back plates were made of Nitronic 40 steel with a Young's Modulus, E of 200 GPa and a Poisson's ratio, ν of 0.3. The contact stiffness kN of the contact surfaces was determined by the following criteria:

$$kN \approx f\, E\, h,$$

where *E* is the Young's modulus of the less stiff contacting material, *h* is the out of plane thickness of the bodies in contact and *f* is a factor varying between 0.01-100. A value of *f* equal to 1 was used for the present simulations.

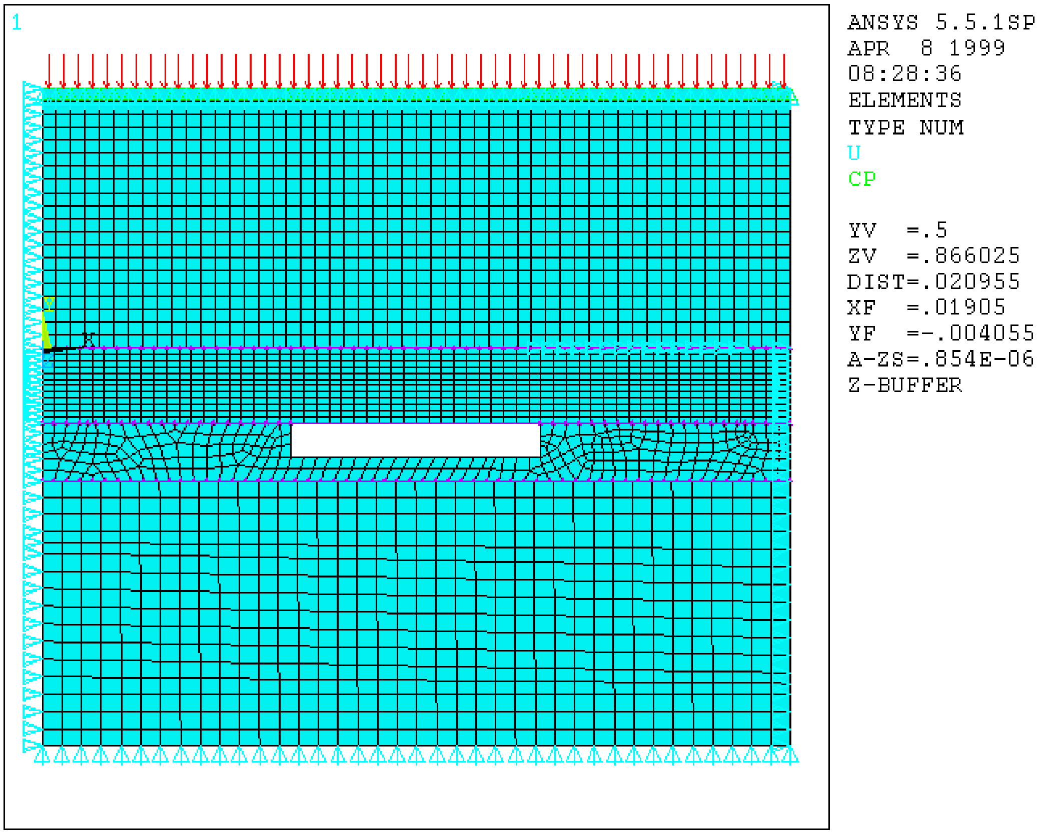

Figure 6: Finite element mesh for beam gauge tested in configuration B.

Fig. 7 compares finite element solutions with the experimental result for configuration *B*. The solid line represents experimental result in this figure. Three different finite element solutions were obtained. For the first case, it was assumed that the beam gauge material remains elastic. For this case, the bending strains in the beam increase linearly with the increase in the applied pressure. However, finite element results for this case do not match well with the experimental results. The second case assumed bilinear isotropic hardening plasticity in the gauge material, with a yield strength of 672 MPa and an ultimate tensile strength of 868 MPa[3]. It is observed that introduction of plasticity in the beam gauge material causes non-linearity in the applied pressure vs. beam deformation behavior. Compared to the elastic solution, same applied pressure causes more bending deformations in the beam gauge for elastic-plastic gauge material. However, our results still do not match well with the experimental results. It was later realized that the beam gauges were made out of annealed Nitronic 40 steel with a yield strength of 413 MPa and an ultimate tensile strength of 800 MPa. Therefore, the finite element model was rerun using the above values. The results of the simulation are shown as solid squares in figure

7. It is observed that the use of correct material properties provides results which match the experimental results extremely well. This gives us confidence in our model.

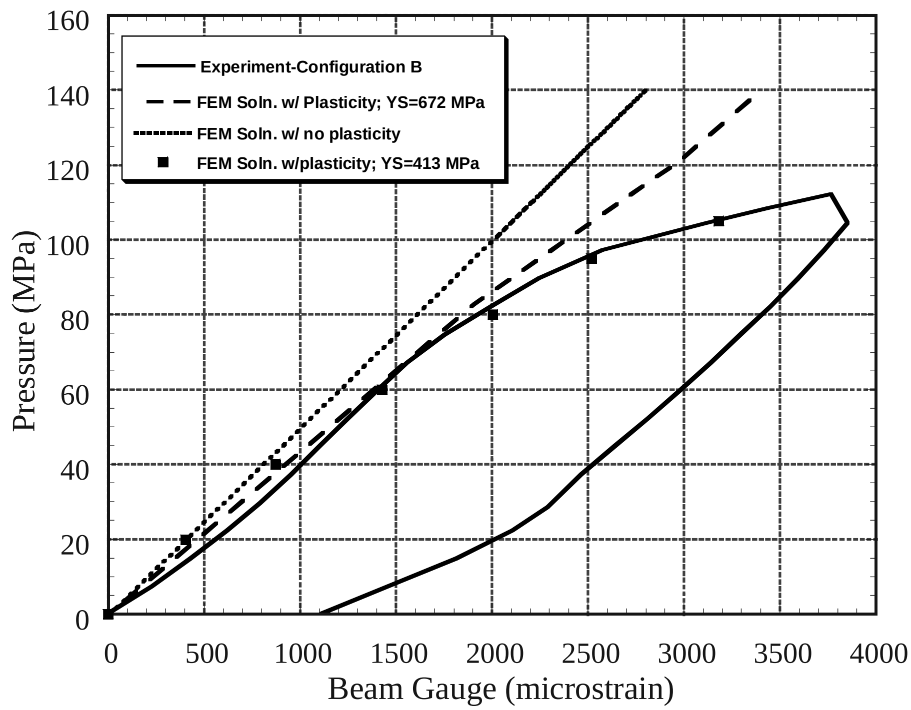

Figure 7: Comparison of experimental results with finite element solutions.

The above results also indicate that very large bending deformations (strains) can occur in the beam gauge if the gauge material can deform plastically. Thus, the difference in behavior observed in Fig. 4 for the two different configurations is primarily due to the plastic deformation of the gauge material in configuration *B*. Also, if the gauge material is assumed to stay elastic, then both configurations *A* and *B* would have almost identical calibration curves. Figures 8 and 9 show the contour plots of von Mises stress and equivalent plastic strain for the beam gauge in configuration *B* for an applied load of 120 MPa. It is observed that very large stresses, more than the yield strength of the gauge material, are produced in certain regions of the beam and back plates. Moreover, the notches in the back plate act as a source of stress concentration. Fig. 9 shows the regions of the beam and back plates which undergo permanent plastic deformation. Plastic strains of the order of 2000 microstrain are observed in the beam plate. This permanent deformation in the beam plate causes a permanent shift in the resistance of the strain gauge. Therefore, pressure values derived from calibration curves obtained in a configuration where no plastic deformation of gauge occurs, give incorrect results.

Fig. 9 also indicates that the back plate undergoes much more severe plastic deformation than the beam plate. An attempt was made to understand the role of permanent deformations of the back plate in influencing the calibration behavior. Therefore, a simulation was run where the beam plate was assumed to stay elastic while the back plate could go plastic if the equivalent stresses in the back plate exceeded its yield strength. The results from this simulation showed that even plastic deformation of the back plate

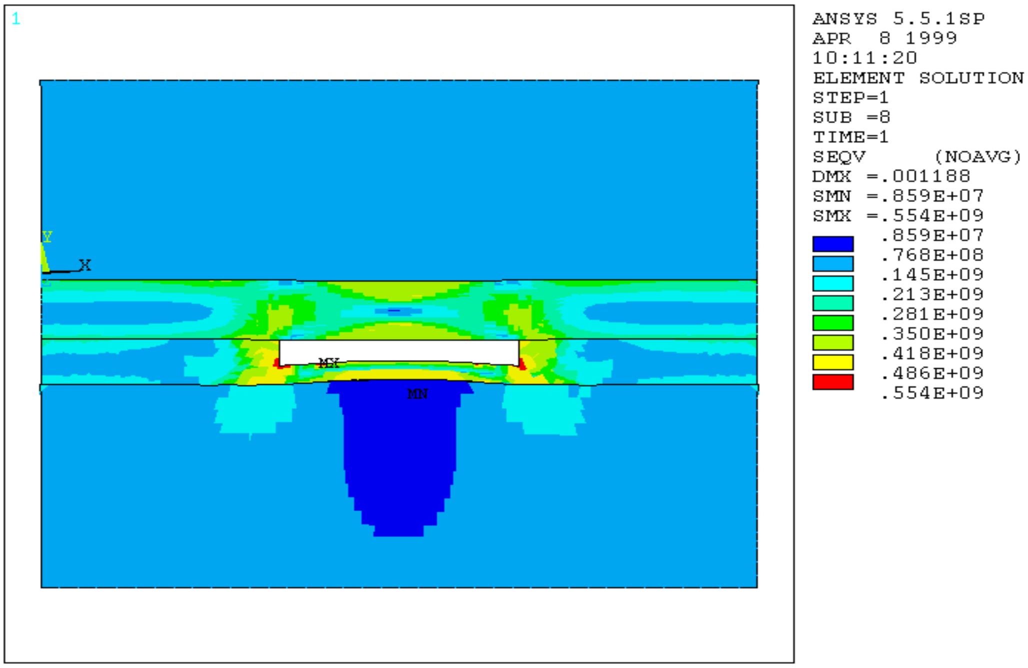

Figure 8: Contour plot of equivalent von Mises stress for an applied pressure of 120 MPa.

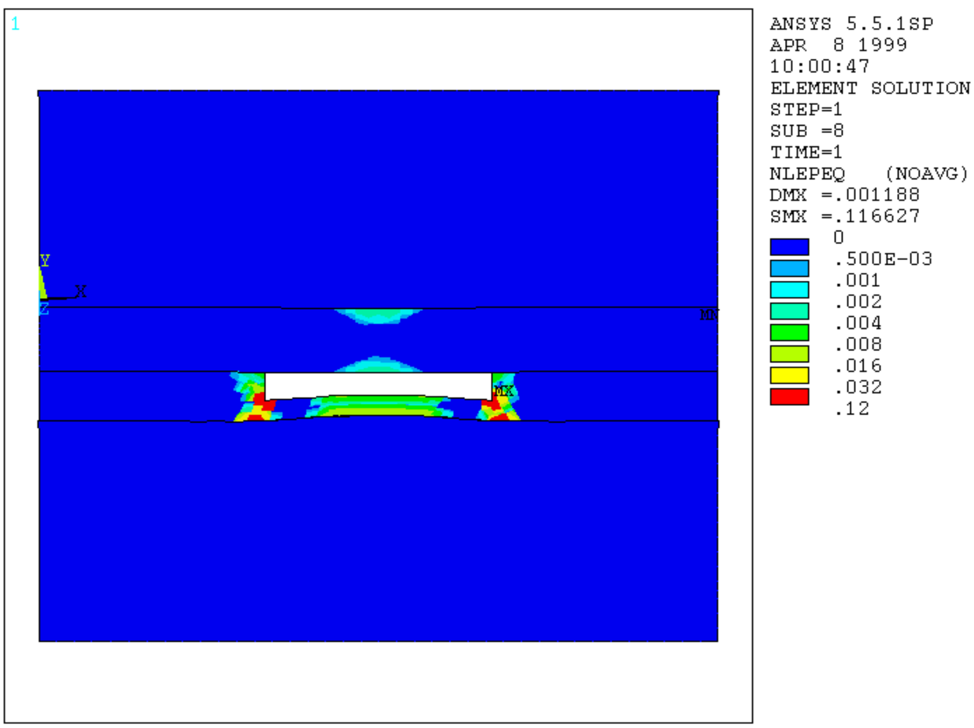

Figure 9: Contour plot of equivalent plastic strain for an applied pressure of 120 MPa.

could cause significant change in the calibration behavior. Thus, it is necessary not only to design beam gauges such that the beam plate remains elastic, but the back plate should also stay elastic for the entire range of applied loads.

The finite element model was also used to investigate the effect of change in the Young's modulus of the ultem block (representing variations in the Young's modulus of the inner and outer coils in a magnet). It was assumed that the gauge material is elastic and the Young's modulus was varied between 3 to 10 GPa. The results from such a calculation are presented in Fig. 10. It is observed that for coil prestress up to 80 MPa, there is not significant change in the calibration curves. This indicates that if the beam gauges are designed to stay elastic for operating loads, then the gauge calibration curves are not much sensitive to the changes in modulus of the magnet coils.

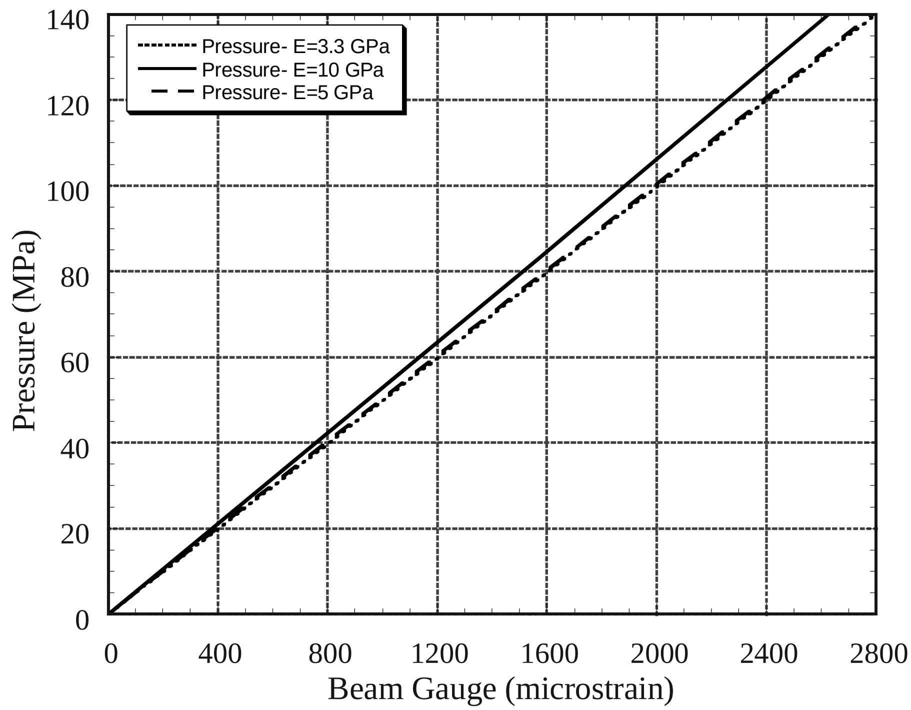

Figure 10: Effect of Young's modulus of ultem on calibration.

5. Conclusions

A finite element model of the beam gauge has been developed to develop a mechanics based understanding of the working of these gauges. The model has been verified with simple experiments performed on a well-characterized material. The model can then be used as a design tool to design beam gauges to measure stresses in the inner and outer coils of a superconducting magnet. It has been shown that calibration of these gauges is very sensitive to the support of the back plate. Also, this sensitivity to the support conditions arises due to plastic deformations in the beam gauge material. Therefore, gauges should be designed such that the gauge material stays elastic for the maximum operating loads in the magnet. Also, it has been shown that the effect of variation in coil modulus on calibration curve is small.

References

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